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Rb-Sr and Sm-Nd isotopic geochronology of the granitoid and hornblende biotite gneiss from Oku-iwa Rock in the Lützow-Holm Complex, East Antarctica

Naoko Nishi[1], Yoshinobu Kawano[2] and Hiroo Kagami[1]

[1]*Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2, Niigata 950-2181*

[2]*Faculty of Culture and Education, Saga University, Honjo 1, Saga 840-8502*

Abstract: Oku-iwa Rock in the Lutzow-Holm Complex, East Antarctica is situated in a transitional between granulite-facies and amphibolite-facies metamorphic zones. Two granite masses, the Akai-misaki mass and the Nishi-kaigan mass are intruded into hornblende biotite gneiss (HB gneiss) in this area. Rb-Sr and Sm-Nd whole rock isochron ages of the HB gneiss are 583±56 Ma and 674±22 Ma, respectively. The Rb-Sr whole rock isochron age of the Akai-misaki granite mass is 485±50 Ma. Some granitoids collected from the Nishi-kaigan granite mass are plotted close to the 485 Ma reference isochron with lower initial $^{87}Sr/^{86}Sr$ ratios then the Akai-misaki granite mass. The HB gneiss was formed from igneous rocks with granodioritic chemical compositions and/or volcanogeneous sedimentary rocks with similar chemical compositions. The HB is characterized by stromatolitic migmatitic appearances. Based on present and previously published geochronological data, the following geochronological sequence for Oku-iwa Rock is estimated. Stage 1 (674±22 Ma) was granodioritic magmatism. Stage 2 (583±56 Ma) has two possible interpretations: (1) the temperature of granodioritic rocks formed at *ca* 670 Ma was gradually lowered and reached *ca* 700°C at 583 Ma, (2) refusion of granodioritic rocks which has formed at 674 Ma took place at 583 Ma. If the migmatitic portions (leucosome) in the HB gneiss was formed at 674 Ma, Oku-iwa Rock must have retained high temperature between *ca* 670 Ma and *ca* 500 Ma (U-Pb zircon ages: *ca* 620 Ma, 560 Ma–520 Ma). Stage 3 (485±50 Ma) was granitic magmatism. After 480 Ma the constitutent rocks of Oku-iwa Rock cooled down, probably caused by uplifting.

key words: Rb-Sr and Sm-Nd geochronology, hornblende biotite gneiss, granitoid, Oku-iwa Rock, Lutzow-Holm Complex

1. Introduction

The Lutzow-Holm Complex (LHC) in East Antarctica consists of amphibolite- to granulite-facies metamorphic rocks accompanied by late Proterozoic to early Paleozoic granitoids. Age data from the LHC have been published by many authors since Maegoya *et al.* (1968). Some age data have been measured by dating methods considered to have high closure temperatures and have been published since the 1980's. Rb-Sr whole rock isochron ages of metamorphic rocks are scattered between 800 Ma and 680 Ma (Shibata *et al*, 1986) U-Pb zircon ages of metamorphic rocks are in the range between 550 Ma and 520 Ma (Shiraishi *et al*, 1994) and *ca* 620 Ma and in the range between 560 Ma and 520 Ma (Fraser, 1997), which have been interpreted as the ages of metamorphism of the LHC (Shiraishi *et al*, 1994, Fraser, 1997) CHIME monazite of the metamorphic rocks has ages of 537 Ma and 533 Ma (Asami *et al*, 1997) K-Ar hornblende ages are scattered, ranging from 600 Ma to 500 Ma, most of them cluster around *ca* 515 Ma (Shibata *et al*, 1985, Fraser and McDougall, 1995) On the other hand, ages of granitoids are scarce Hornblende in the granitoid from East Ongul Island gives a Rb-Sr age of 482 5±9 5 Ma (Shibata *et al*, 1985) K-Ar biotites of the granitoids from the LHC give ages between 449 Ma and 399 Ma (Yanai and Ueda, 1974, Fraser and McDougall, 1995) Biotite, K-feldspar and plagioclase separated from granitoids of Oku-iwa Rock and Cape Omega give well defined Rb-Sr isochrons with ages of 417 9±2 2 Ma and 439 0±12 3 Ma, respectively (Nishi *et al*, 1999) Closure temperatures of K-Ar and Rb-Sr biotite ages are *ca* 300°C (Wagner *et al*, 1977, Harrison *et al*, 1985, Nishimura and Nogi, 1986), whereas that of K-Ar hornblende is *ca* 500°C (Harrison, 1981, Nishimura and Nogi, 1986) Thus, these mineral ages indicate the cooling stage of granitoids and do not indicate the activity stage of granitic magmas The ages of igneous activity are probably obtained by dating methods with high closure temperature such as Rb-Sr and Sm-Nd whole rock isochrons, U-Pb zircon and so on The age data of the granitoids measured by dating methods with high closure temperature are quite few (*e g.* Shimura *et al*, 1998) As the granitoids are one of the important constituting rocks of the LHC, their activity ages have significant meaning in analyzing the formation process of the complex We discuss the meaning of measured Rb-Sr and Sm-Nd whole rock isochron ages of the granitoid and gneiss in order to establish the thermochronological sequence of Oku-iwa Rock

2. Outline of geology of Oku-iwa Rock

Oku-iwa Rock on the Prince Olav Coast is situated in the transitional zone between granulite-facies and amphibolite-facies metamorphic zones (Hiroi *et al*, 1983a) (Fig 1a) The metamorphic rocks in this area are divided into three members based on their mode of occurrence, petrographical characteristics, folding structures and degree of migmatization The three members have a foliation with general trend indicating E-W strike and 50–80°S dip (Nakai *et al*, 1981)

The lowermost member is hornblende biotite gneiss, which is widely exposed in the northern area (Fig 1b) The gneiss is subdivided into two rock types melanocratic fine-grained rocks and leucocratic fine- to coarse-grained rocks (Nakai *et al*, 1981) Both rock types contain leucosomes which are 5 to 20 cm thick and are cross-cut by granite dykes (Fig 2a, b) The middle member is migmatitic biotite hornblende gneiss which occupies the central part of the area (Fig 1b) The uppermost member is leucocratic biotite gneiss, which is exposed in the southern part of the area

The granitoids intrude into hornblende biotite gneiss, forming two discordant masses and narrow dykes on the northern seashore of Oku-iwa Rock (Fig 1b) The eastern mass is exposed about 0 035 km^2 and the western mass crops out in an area of approximately 0 005 km^2 (Fig 1b) The former and latter are tentatively named the "Akai-misaki"

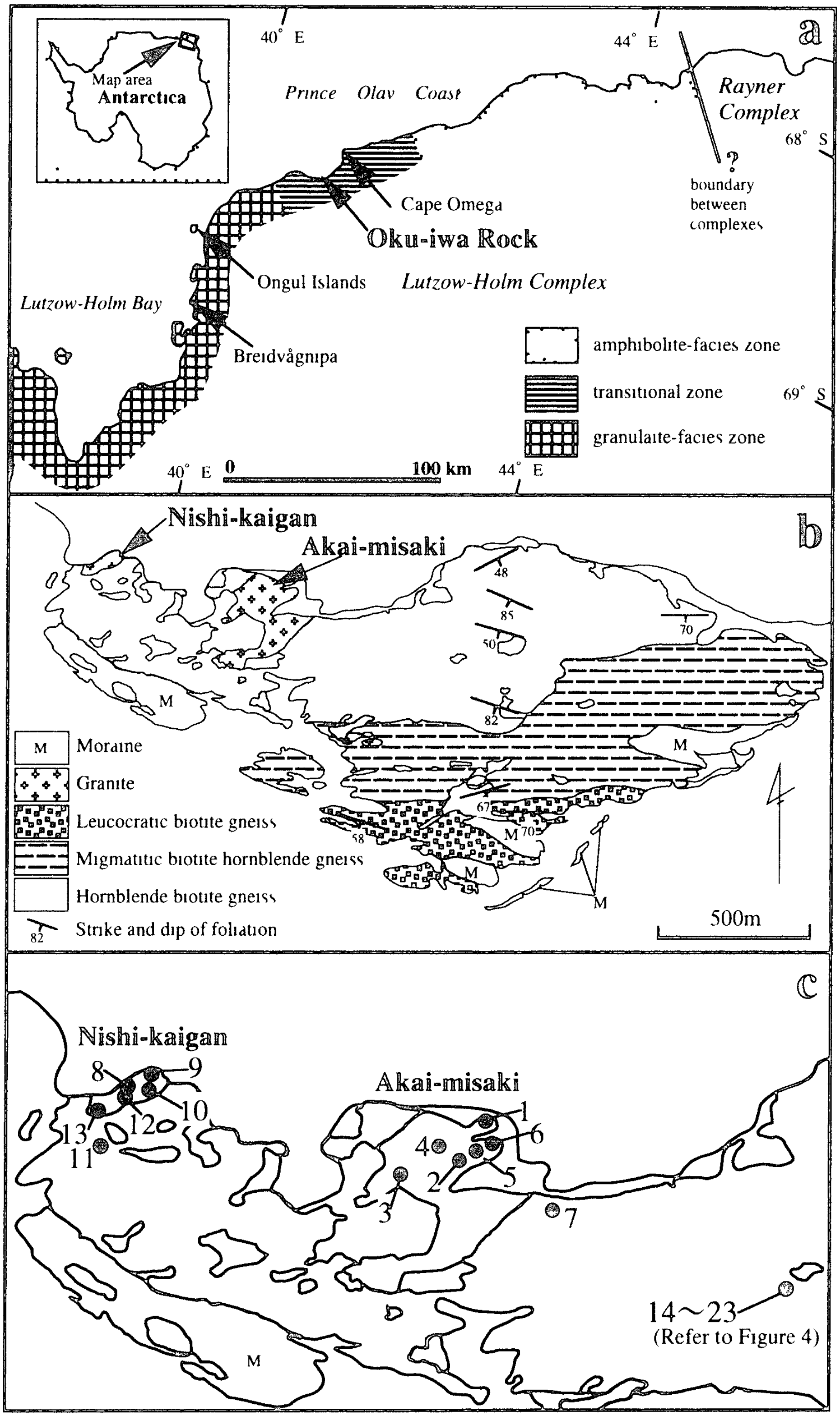

Fig 1 Geological map of the study area (a, b) (simplified from Nakai et al, 1981) and sampling sites of analyzed samples (c) Metamorphic boundaries are after Hiroi et al (1991)

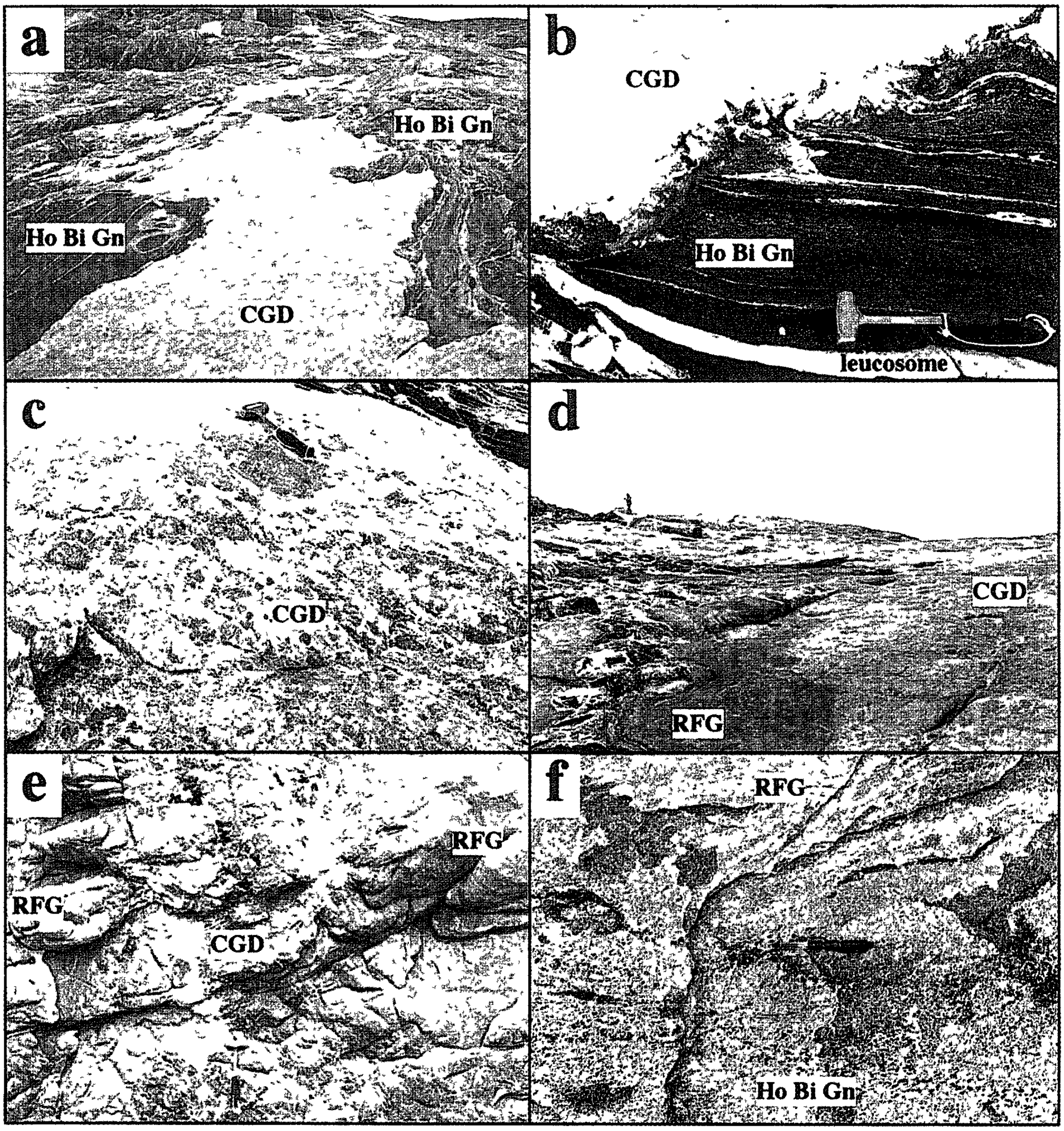

Fıg 2 Modes of field occurrence of Akaı-mısakı and Nıshı-kaıgan granıte masses
a Granıte dyke cross-cuts the gneıssıc fabrıc (mıddle part of photograph) Note that the granıte has an ırregular boundary wıth the host gneıss but the granıte ıs not deformed b The bıotıte granıte of the Akaı-mısakı granıte mass cross-cuts lucosomes c The reddısh fine-graıned granıte develops at margın of the Akaı-mısakı mass d Mode of occurrence of the coarse-graıned granıte and granodıorıte ın the Akaı-mısakı mass e The fine-graıned granıte ıs cross-cut by the coarse-graıned granıtoıds ın the Nıshı-kaıgan mass f The fine-graıned granıte shows weak folıatıon ın the Nıshı-kaıgan mass RFG reddısh fine-graıned granıte, CGD coarse-graıned granıte and granodıorıte, Ho Bı Gn hornblende bıotıte gneıss

granıte mass and the "Nıshı-kaıgan" granıte mass, respectıvely The granıte dykes derıved from the granıte masses cross-cut gneıssose structures subparallel to leucosomes of the hornblende bıotıte gneıss havıng leucosomes (Fıg 2a, b)

3. Descriptions of analyzed samples

Thirteen granitoids were selected for isotope analysis The Akai-misaki granite mass consists of mainly coarse-grained biotite granite to granodiorite accompanied by reddish fine-grained biotite granite The coarse-grained granitoid has no foliations and is characterized by reddish K-feldspar megacryst up to 10 cm long (Fig 2c) The reddish fine-grained granitoid develops at the margin of the mass and locally has weak foliation defined by alignment of biotite (Fig 2d) The coarse-grained and fine-grained granitoids are intergradational, however, the latter is partly intruded by the former On the other hand, the Nishi-kaigan granite mass is composed of fine-grained biotite granite and coarse-grained biotite granite to granodiorite Relationship between these granitoids is similar to those in the Akai-misaki granite mass (Fig 2e) The fine-grained granitoid of the Nishi-kaigan granite mass also has weak foliation (Fig 2f), whereas the coarse-grained granitoid shows no structure The coarse-grained granite and granodiorite are composed of quartz (modal composition, 28–43%), K-feldspar (14–68%), plagioclase (14–44%), biotite (0–2%) and muscovite (0–0 5%) (Fig 3a) The fine-grained granite is comparatively equigranular rock and its constituents are quartz (32–38%), K-feldspar (46–52%), plagio-

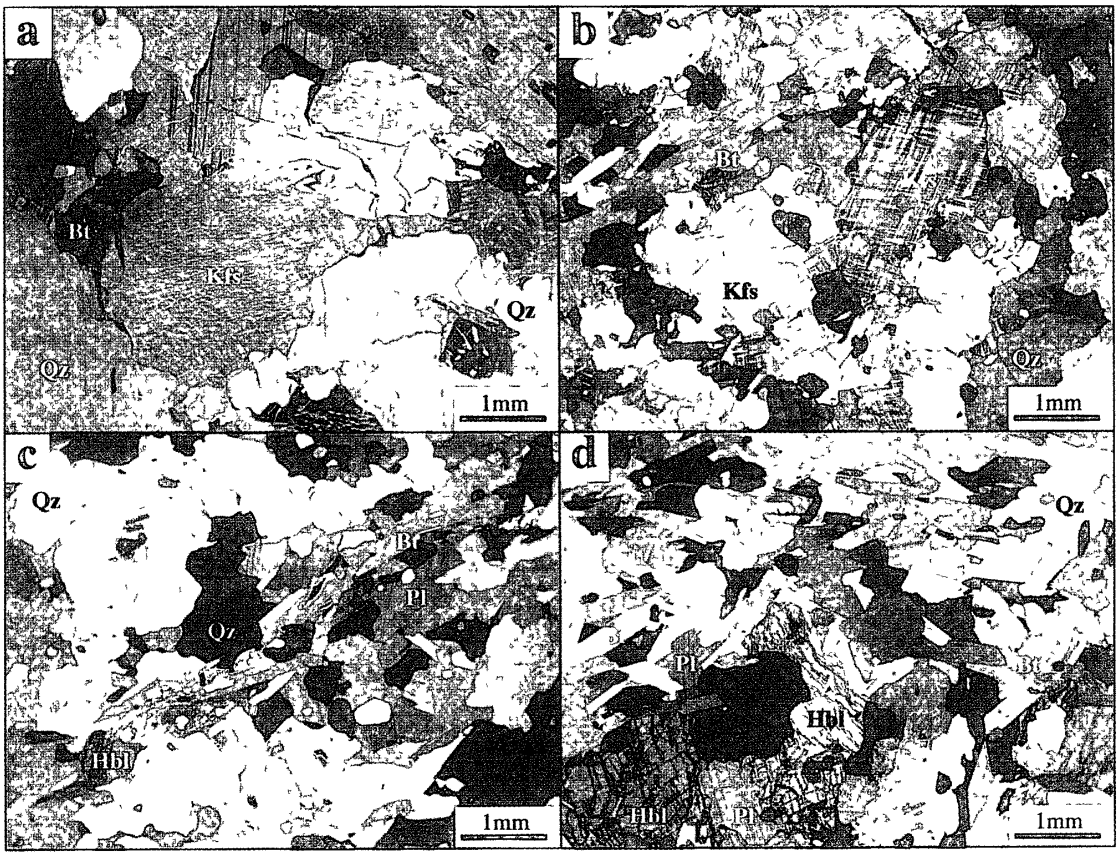

Fig 3 Photomicrographs of granitoids and hornblende biotite gneiss a coarse-grained granite (sample 4, Akai-misaki granite mass), b reddish fine-grained granite (sample 9, Nishi-kaigan granite mass), c hornblende biotite gneiss (sample 17), d hornblende biotite gneiss (sample 21) Hbl hornblende, Bt biotite, Pl plagioclase, Kf K-feldspar, Qz quartz

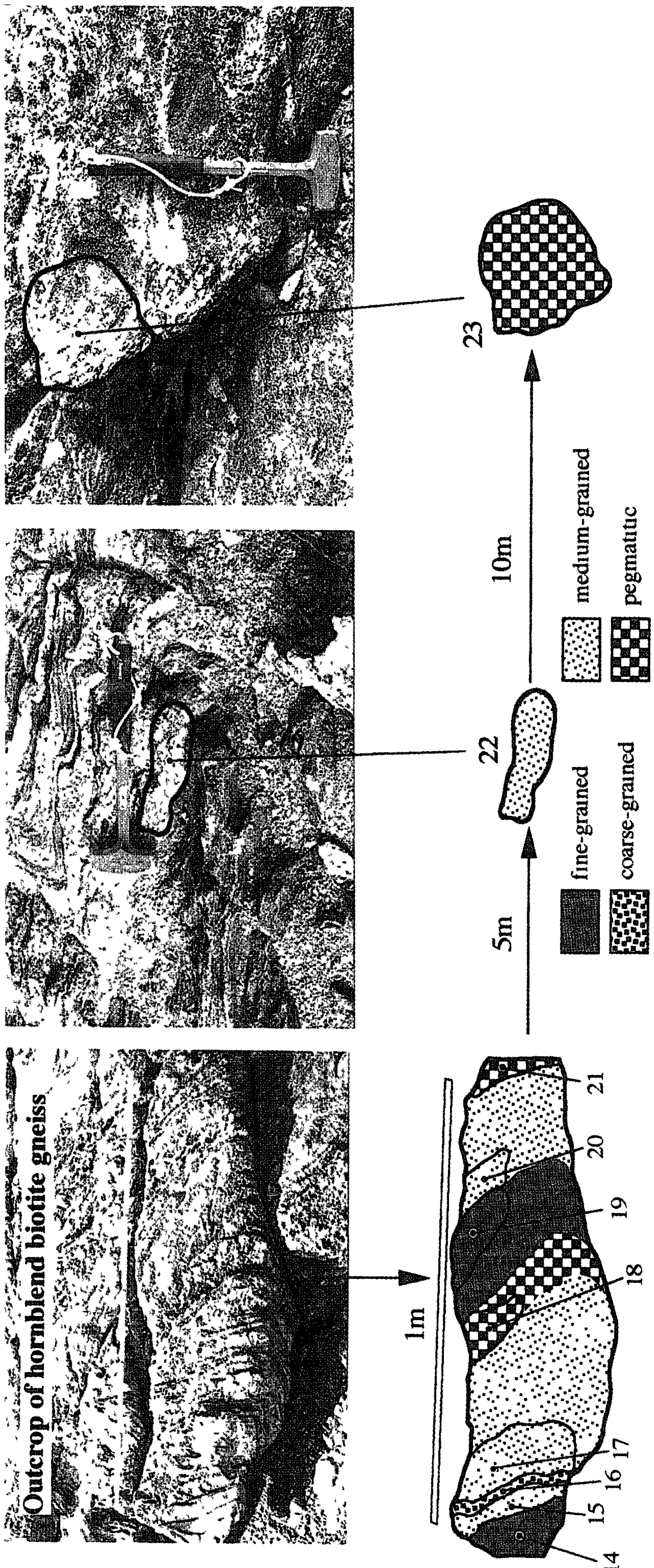

Fig 4 *Outcrops of hornblende biotite gneiss and analyzed samples*

Table 1 Major and minor elements of hornblende biotite gneiss in Oku-iwa Rock

	Hornblende biotite gneiss									
Sample No	14	15	16	17	18	19	20	21	22	23
Sample Name	K950110m1	K950110m2	K950110m3	K950110m4	K950110m5	K950110m6	K950110m7	K950110m8	K950110m9	K950110m10
SiO_2	68.62	65.11	66.86	68.61	69.26	69.88	69.32	65.49	69.59	69.19
TiO_2	0.66	0.92	0.83	0.81	0.76	0.45	0.69	0.90	0.57	0.55
Al_2O_3	14.80	14.21	14.00	13.62	13.45	15.67	14.81	13.38	13.48	14.84
Fe_2O_3*	4.58	7.10	6.26	6.15	6.16	3.05	4.10	6.80	6.09	4.41
MnO	0.12	0.22	0.19	0.13	0.13	0.07	0.10	0.25	0.14	0.07
MgO	1.79	2.81	2.48	2.01	1.76	1.14	1.73	3.41	1.40	1.48
CaO	2.96	3.35	3.19	2.48	2.47	2.80	2.59	3.31	2.95	2.29
Na_2O	4.50	3.98	4.06	3.93	3.96	5.09	4.43	3.54	4.06	3.97
K_2O	1.78	2.00	1.86	2.02	1.83	1.70	2.02	2.35	1.53	3.14
P_2O_5	0.19	0.30	0.27	0.24	0.22	0.15	0.21	0.57	0.19	0.06
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Ba	718	761	718	813	754	656	856	1038	676	1262
Cr	18	24	21	15	11	18	18	125	20	46
Nb	5	7	6	5	4	3	5	9	4	6
Ni	3	4	4	—	6	—	—	26	—	4
Rb	53	62	58	68	59	44	63	80	43	95
Sr	297	247	251	244	247	317	284	211	346	467
V	70	106	98	47	53	41	58	100	95	87
Y	22	61	52	23	23	11	16	55	28	6
Zr	173	142	134	183	159	231	195	225	226	88
DF3	1.97	0.47	0.65	—	0.33	—	—	-0.57	—	1.80
DF4	2.33	3.25	3.02	—	2.23	—	—	-0.07	—	2.57

Sample Nos are same as those in Fig 1c. DF3 and DF4 values after Shaw (1972) are calculated using the following equation
$DF3 = 10.44 - 0.21SiO_2 - 0.32Fe_2O_3^* - 0.98MgO + 0.55CaO + 1.46Na_2O + 0.54K_2O$,
$DF4 = -39.59 + 0.42SiO_2 + 0.30Fe_2O_3^* + 0.89MgO + 1.53CaO + 0.58Na_2O + 2.07K_2O - 0.037Cr + 0.005V - 0.027Ni - 0.001Sr$ (* Total Fe as Fe_2O_3)

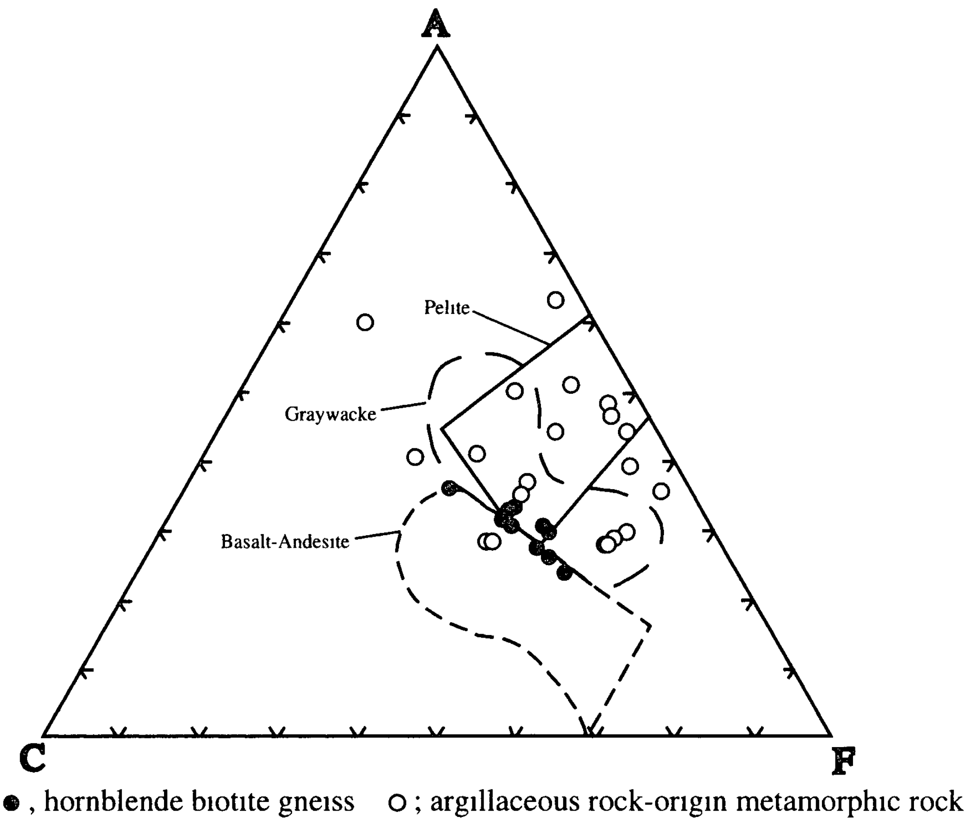

Fig 5 *ACF diagram after Winkler (1979) of hornblende biotite gneisses in the Oku-iwa Rock and argillaceous rock-origin metamorphic rocks in the LHC Data sources This study, Banno et al (1964), Yoshida et al (1976), Yoshida (1978), Kanisawa et al (1979), Nakai et al (1980), Hiroi et al (1983b), Motoyoshi et al (1986), Shiraishi (unpublished data)*

clase (11–14%), biotite (2–4%) and muscovite (0–0 5%) (Fig 3b)

Ten samples of hornblende biotite gneiss (abbreviated to HB gneiss hereafter) for isotope analysis were collected from a single outcrop in the lowermost member Photomicrographs of the gneiss are shown in Fig 3c and d For elucidation of the closure system in Rb-Sr and Sm-Nd isotopic geochronology, eight samples Sp Nos 14–21 were collected within about 1 m Sp Nos 22 and 23 were collected from the outcrop 5 m and 15 m away from Sp No 21, respectively (Fig 4) They are composed of quartz (40–54%), K-feldspar (4–9%), plagioclase (24–39%), biotite (7–21%) and hornblende (0–11%) Magnetite and ilmenite occur as accessory minerals (~2%)

Major and minor chemical compositions of the HB gneisses are given in Table 1 We estimate whether the protolith of the HB gneiss is igneous rock or sedimentary rock based on the method of Osanai *et al* (1992) DF3 and DF4 values of the gneiss after Shaw (1972) are positive (Table 1) except Sp No 21, which is inferred to be the igneous rock for the protolith At this point, HB gneiss meets the requirements ($Na_2O \leq 6$ 5 wt%, $K_2O \leq 7$ 3 wt%, $10 \leq Al_2O_3 \leq 19$ wt%, $50 \leq SiO_2 \leq 80$ wt%) for calculation of the DF3 and DF4 values In the ACF diagram of Winkler (1979), some HB gneisses are plotted in the basalt-andesite field, and some others around the boundary between the greywack and basalt-andesite fields (Fig 5)

4. Analytical procedures

Extraction procedures for Sr, Sm and Nd from rock powders have been discussed by Kagami *et al* (1982, 1987) Isotopic analyses were performed on MAT261-type (modified from MAT260) and MAT262 mass spectrometers at Niigata University The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{86}Sr/^{88}Sr = 0\ 1194$ and $^{146}Nd/^{144}Nd = 0\ 7219$, respectively The $^{87}Sr/^{86}Sr$ ratio of NBS987 during this study was $0\ 710172 \pm 0\ 000014$ (2σ, $n=13$) The $^{87}Sr/^{86}Sr$ ratios in Table 2 were reported relative to NBS987 = 0 710218 (Nishi *et al*, 1999) $^{143}Nd/^{144}Nd$ ratios in Table 2 were reported relative to 0 512115 (JNdi-1, Geological Survey of Japan standard) corresponding to 0 511858 of LaJolla (Tanaka *et al*, 2000) The blanks for the whole procedures were 27 pg of Sm, 270 pg of Nd and 450 pg of Sr Concentrations of major and minor elements including Rb and Sr were determined by XRF (RIX3000, Niigata University, RIX2000, Fukuoka University of Education) according to the procedure of Takahashi and Shuto (1997) The ages and initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were calculated by the computer program of Kawano (1994) using the equation of York (1966) and the following decay constant $\lambda^{87}Rb = 1\ 42 \times 10^{-11} y^{-1}$ (Steiger and Jager, 1977) and $\lambda^{147}Sm = 6\ 54 \times 10^{-12} y^{-1}$ (Lugmair and Marti, 1978) The estimated relative errors in the age calculation of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios are 5% (1σ) and 0 015% (1σ), respectively Likewise, the errors of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios are 0 2% (1σ) and 0 010% (1σ), respectively Initial εNd values were calculated using the following CHUR parameters, $^{147}Sm/^{144}Nd_{(0\ Ma)} = 0\ 1966$, $^{143}Nd/^{144}Nd_{(0\ Ma)} = 0\ 512638$ Nd model ages were calculated using the following depleted-mantle parameters $^{147}Sm/^{144}Nd_{(0\ Ma)} = 0\ 2136$, $^{143}Nd/^{144}Nd_{(0\ Ma)} = 0\ 51315$ ($\varepsilon Nd = +10$)

5. Results

5 1 Rb-Sr whole rock isochron age of granitoids

Sample locations of granitoids and HB gneisses are shown in Fig 1c The analytical results are listed in Table 2 Seven whole rock samples (Sp No 1-7) from the Akai-misaki granite mass give a Rb-Sr isochron age of 506 ± 60 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of $0\ 70604 \pm 0\ 00029$ (MSWD = 2 34) Sp No 7 was collected from out of the Akai-misaki

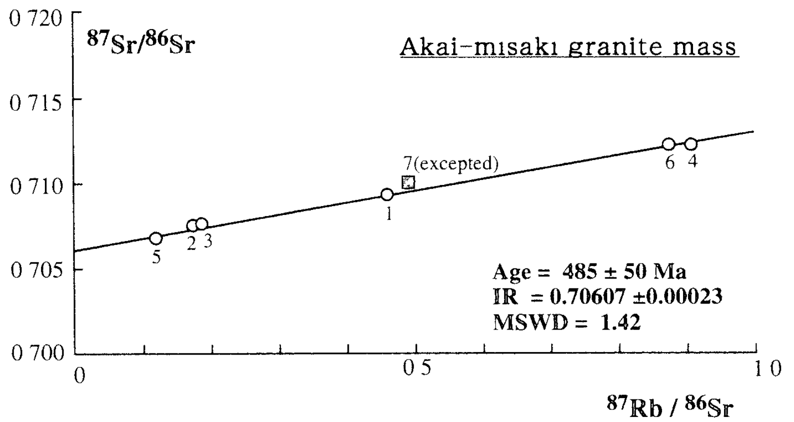

Fig 6 Rb-Sr whole rock isochron diagram of Akai-misaki granite mass IR initial $^{87}Sr/^{86}Sr$ ratio

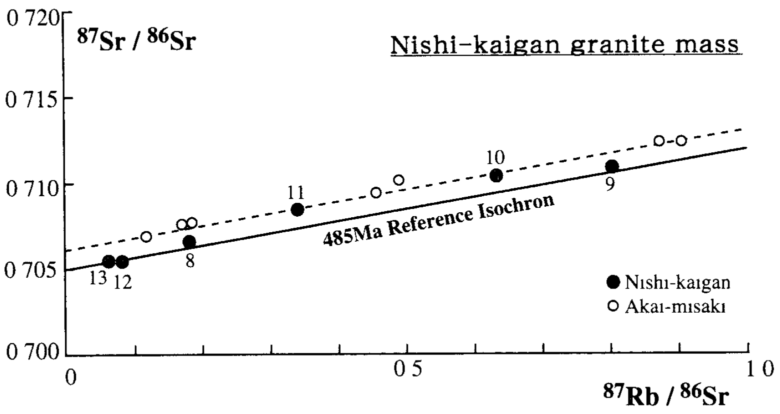

Fig 7 Rb-Sr whole rock isochron diagram of Nishi-kaigan granite mass Broken line indicates isochron of the Akai-misaki granite mass Open circles Akai-misaki granite

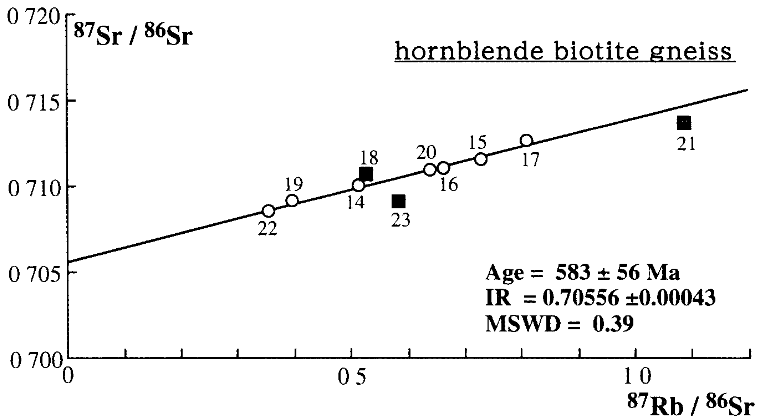

Fig 8 Rb-Sr whole rock isochron diagram of hornblende biotite gneiss

granite mass (Fig 1c) Six samples (all except No 7) give an age of 485±50 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0 70607±0 00023 (MSWD=1 42, Fig 6) We cited 485 Ma as the age of the Akai-misaki granite mass, taking into account the sampling location of Sp No 7 and low MSWD value Biotite, K-feldspar and plagioclase separated from No 3 yield the age of 417 9±2 2 Ma in the Rb-Sr system (Nishi *et al* , 1999) Age interval between 485 Ma and 418 Ma is significant for analyzing the cooling history of the granite mass as previously discussed by Nishi *et al* (1999) Six samples (Sp Nos 8–13) were collected from the Nishi-kaigan granite mass, which is situated *ca* 500 m west of the Akai-misaki granite mass (Fig 1) A definite isochron age is not obtained from this granite mass because of scattering of isotopic data Four data (Sp Nos 8, 9, 12, 13) are plotted close to the 485 Ma isochron defined by the Akai-misaki granite and lie on a slightly steeper line than the isochron, but the line is obviously below the 485 Ma isochron Therefore, we show a reference isochron in Fig 7 for the Nishi-kaigan granite mass Samples No 10 and No 11 are close to the isochron of the Akai-misaki granite mass

Table 2 Rb, Sr, Sm and Nd concentrations and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios of granitoids and metamorphic rocks Sample Nos are same as those in Fig 1c

	Sp No	Sample Name	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{DM}(Ma)
Akai-misaki granite	1	K95010802	82	513	0 463	0 709273(14)	—	—	—	—	—
	2	K95010803	35	573	0 177	0 707422(12)	—	—	—	—	—
	3	K95010804	124	1888	0 190	0 707509(15)	22 8	163	0 0840	0 511928(11)	—
	4	K95010805	132	420	0 910	0 712145(12)	—	—	—	—	—
	5	K95011001	25	589	0 123	0 706718(14)	—	—	—	—	—
	6	K95011002	125	412	0 878	0 712164(12)	—	—	—	—	—
	7	K95011004	70	410	0 494	0 710021(11)	—	—	—	—	—
Nishi-kaigan granite	8	K95010902	58	912	0 184	0 706523(14)	—	—	—	—	—
	9	K95010903	99	357	0 803	0 710727(12)	—	—	—	—	—
	10	A95010902	109	493	0 639	0 710353(12)	—	—	—	—	—
	11	A95010905	146	1229	0 344	0 7082050(8)	—	—	—	—	—
	12	A95010907	20	713	0 083	0 705140(14)	—	—	—	—	—
	13	OK04	10	471	0 064	0 705344(13)	—	—	—	—	—
hornblende biotite gneiss	14	K950110m1	53	297	0 518	0 709909(13)	—	—	—	—	—
	15	K950110m2	62	247	0 732	0 711405(13)	7 37	26 0	0 1714	0 512680(18)	—
	16	K950110m3	58	251	0 666	0 710968(14)	6 48	22 9	0 1710	0 512679(20)	—
	17	K950110m4	68	244	0 813	0 712583(12)	4 23	18 4	0 1388	0 512533(14)	—
	18	K950110m5	59	247	0 530	0 710694(13)	—	—	—	—	—
	19	K950110m6	44	317	0 401	0 709047(13)	3 94	23 0	0 1039	0 512378(64)	1070
	20	K950110m7	63	284	0 642	0 710822(14)	5 19	29 3	0 1072	0 512400(16)	1070
	21	K950110m8	80	211	1 09	0 713675(13)	8 79	33 3	0 1597	0 512482(24)	—
	22	K950110m9	43	346	0 359	0 708449(10)	4 33	18 1	0 1447	0 512553(35)	—
	23	K950110m10	95	467	0 587	0 709035(11)	1 50	9 39	0 0967	0 512263(24)	1160

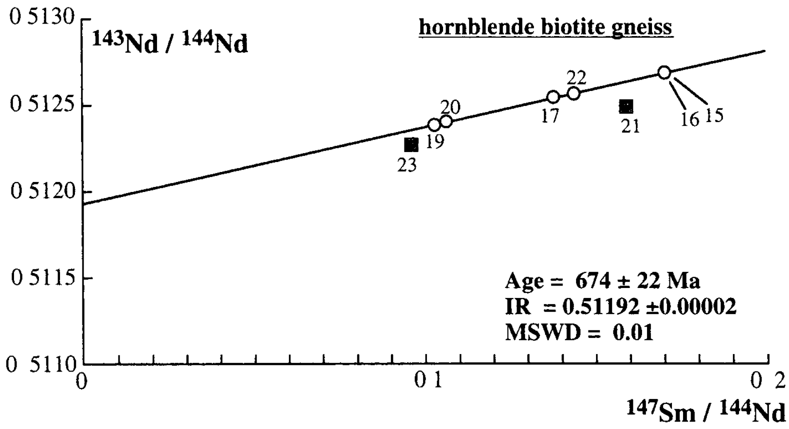

Fıg 9 Sm-Nd whole rock ısochron dıagram of hornblende bıotıte gneıss IR ınıtıal ^{143}Nd/^{144}Nd ratıo

Table 3 1000/Sr and 100/Nd values, and ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratıos at 540 Ma, 583 Ma and 674 Ma of hornblende bıotıte gneıss

Sample No	Sample Name	1000/Sr	^{87}Sr/^{86}Sr (540 Ma)	^{87}Sr/^{86}Sr (583 Ma)	^{87}Sr/^{86}Sr (674 Ma)	100/Nd	^{143}Nd/^{144}Nd (540 Ma)	^{143}Nd/^{144}Nd (583 Ma)	^{143}Nd/^{144}Nd (674 Ma)
14	K950110m1	3 37	0 705922	0 705602	0 704928	–	–	–	–
15	K950110m2	4 05	0 705770	0 705320	0 704366	3 85	0 512074	0 512025	0 511923
16	K950110m3	3 98	0 705841	0 705432	0 704563	4 37	0 512074	0 512026	0 511924
17	K950110m4	4 10	0 706325	0 705825	0 704765	5 43	0 512042	0 512003	0 511920
19	K950110m6	3 15	0 705960	0 705714	0 705191	4 35	0 51201	0 511981	0 511919
20	K950110m7	3 52	0 705880	0 705485	0 704648	3 41	0 512021	0 511990	0 511926
22	K950110m9	2 89	0 705686	0 705465	0 704997	5 52	0 512041	0 512000	0 511914
mean	–	–	–	0 705549*	0 704780	–	–	–	0 511921

* Mean value ıs slıghtly dıfferent from ınıtıal ^{87}Sr/^{86}Sr of 0 70556 whıch was calculated by an age determınatıon pıogram (Fıg 8)

5.2. Rb-Sr and Sm-Nd whole rock isochron ages of hornblende bıotıte gneiss

Ten HB gneıss samples were collected from a sıngle outcrop A relıable Rb-Sr whole rock ısochron ıs not defined because of scatterıng flock of the ısotopıc data We examıned the samplıng posıtıons and rock facıes Sample No 23 collected from a sıte far from the other nıne samples (Nos 14–22) ıs a pegmatıtıc rock Samples No 18 and No 21 are also pegmatıtıc rocks as shown ın Fıg 4 The Rb and Sr ısotopıc data for these samples (Nos 18, 21, 23) do probably not ındicate whole rock data of each sample because of too coarse-graıned rocks Alternatıvely, they were derıved from dıfferent sources from the other seven samples The seven samples (No 14, 15–17, 19, 20, 22) gıve an ısochron age of 583$\pm$56 Ma wıth an ınıtıal ^{87}Sr/^{86}Sr ratıo of 0 70556$\pm$0 00043 (MSWD=0 39, Fıg 8) We analyzed Sm and Nd ısotopıc data of eıght HB gneısses (Table 2) Sıx samples (Nos 15–17, 19, 20, 22) gıve a relıable straıght lıne wıth an age of 674$\pm$22 Ma (ınıtıal ^{143}Nd/^{144}Nd=0 511921$\pm$0 000021, MSWD=0 01, Fıg 9), whereas two samples (Nos 21, 23) are off of thıs lıne as well as out of the Rb-Sr system

We examıne the possıbılıty of pseudo-ısochron (mıxıng lıne) for the lıne wıth an ınclınatıons ındıcatıng the age of 583 Ma The sımple mean of the metamorphıc ages for the LHC (550 Ma–520 Ma, Shıraıshı *et al*, 1994, 560 Ma–520 Ma, Fraser, 1997) ıs 540 Ma

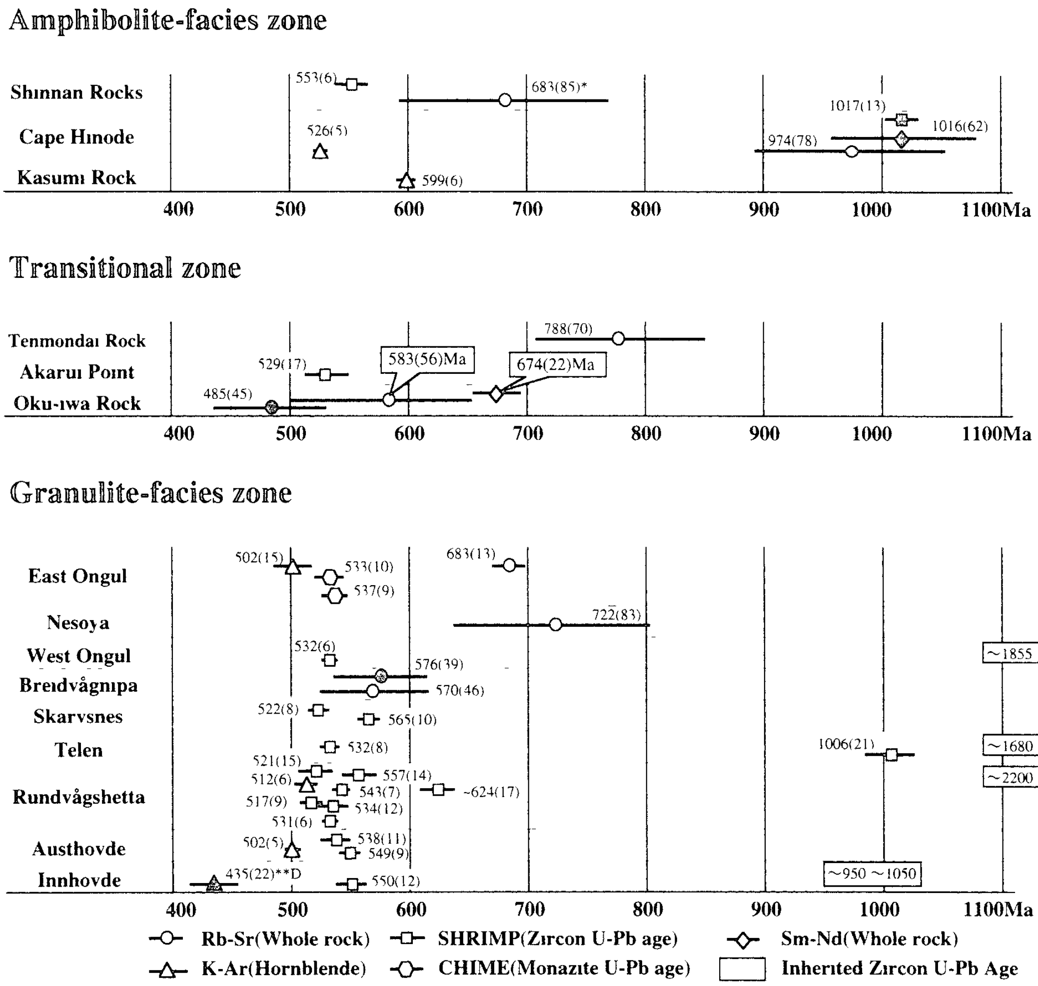

Fig 10 *Ages of metamorphic rock and granitoids occurring in the Lutzow-Holm Complex Age data were measured by dating systems with high closure temperature * Isotopic data are partially scattered Open symbols are metamorphic rock and closed symboles are igneous rock **D Dyke of ultrapotassic mafic igneous rock Data sources This study, Shibata et al, 1985, 1986, Nakajima et al, 1988, Shiraishi et al, 1992, 1994, 1995, Arima and Shiraishi, 1993, Fraser and McDougall, 1995, Asami et al, 1997, Fraser, 1997, Shimura et al, 1998*

The $^{87}Sr/^{86}Sr_{(I)}$ *vs* 1/Sr [and $^{143}Nd/^{144}Nd_{(I)}$ *vs* 1/Nd] relation is important to judge whether the straight line obtained in the Rb-Sr (Sm-Nd) isochron diagram is a mixing line or not If the straight line is obtained in the $^{87}Sr/^{86}Sr_{(I)}$ *vs* 1/Sr diagram, the straight line in the isochron diagram is interpreted as a mixing line (*eg* Faure, 1977, 2001, Dickin, 1995) Any definite relationship between $^{87}Sr/^{86}Sr$ (540 Ma) and 1000/Sr is not recognized in the numerical values in Table 3 This fact excludes the possibility of a mixing line On the other hand, the Sm-Nd whole rock isochron showing 674 Ma is well defined by the HB gneiss (Fig 9) No definite tendency for the relationship between $^{143}Nd/^{144}Nd$ (583 Ma, 540 Ma) and 100/Nd for this gneiss is recognized (Table 3) This suggests that the line indicating 674 Ma is not a mixing line

Several Rb-Sr whole rock isochron ages of *ca* 700 Ma are shown in Fig 10 However, it is necessary to reexamine in detail whether they are real ages or not because they have a straight relation in the $^{87}Sr/^{86}Sr_{(540\,Ma)}$ *vs* 1/Sr diagrams which are not shown in this paper

6. Discussion

6.1. Age data of the Lützow-Holm Complex

Figure 10 shows the age results of this study as well as previously published data for LHC which are considered to have high closure temperature The age data measured by dating methods with low closure temperature are not shown in the figure though they range from *ca* 450 Ma to *ca* 400 Ma The following ages and events can be read out of this figure, that is, (1) inherited zircons late Archean to middle Proterozoic events, (2) some igneous and metamorphic rocks *ca* 1000 Ma (Grenville event), (3) igneous-origin metamorphic rocks *ca* 670 Ma & *ca* 620 Ma (Pan-African event), (4) some other metamorphic rocks and granitoids *ca* 590Ma–*ca* 480 Ma (Pan-African event), (5) ultrapotassic igneous dyke *ca* 430 Ma

6 2. Intrusive age of granitoids

The Rb-Sr whole rock isochron age of 485±50 Ma (Fig 6) for the Akai-misaki granite mass is older than the biotite mineral isochron age of 417 9±2 2 Ma (Nishi *et al* , 1999) and younger than the U-Pb zircon and CHIME monazite ages (550 Ma–520 Ma) of the LHC Granite dykes derived from the Akai-misaki and Nishi-kaigan granite masses cross-cut the gneissose structure of the HB gneiss (Fig 2a, b) Considering this field evidence, the Rb-Sr whole rock isochron of the Akai-misaki granite mass is close to the intrusive age of granitic magma after metamorphism On the other hand, a reliable age is not obtained from the Nishi-kaigan granite mass because of heterogeneous initial Sr isotopic compositions Some samples are close to the isochron of 485 Ma defined by the Akai-misaki granite mass, whereas some other samples are close to another 485 Ma line with different initial $^{87}Sr/^{86}Sr$ ratio (Fig 7) These data suggest that the activity age of the Nishi-kaigan granite mass is similar to that of the Akai-misaki granite mass, but it was derived from a different source Furthermore, we measured the Nd isotopic composition of one sample (No 3) (Table 2) The granite masses have no genetical relation to the HB gneiss, because the initial $^{143}Nd/^{144}Nd$ ratio (0 51166) calculated using an age of 485 Ma for the sample is quite different from that (mean value of Sp No 15–17, 19–23, 0 51206± 0 00007 (1σ)) of the gneiss

Rb-Sr biotite ages of granitoids from Oku-iwa Rock and Cape Omega are *ca* 420 Ma–*ca* 440 Ma, which overlap with *ca* 450 Ma–*ca* 400 Ma of K-Ar biotite ages for the granitoids and metamorphic rocks of the LHC These Rb-Sr and K-Ar age data indicate that the cooling rate of the LHC between *ca* 450 Ma and *ca* 400 Ma was around 6°C/Ma

6 3. Interpretations of Rb-Sr and Sm-Nd whole rock isochron ages of hornblende biotite gneiss

The HB gneiss having 65–70 SiO_2 wt% (Table 1) gives a Rb-Sr whole rock age of 583±56 Ma (Fig 8), which seems to be slightly older than the SHRIMP zircon and CHIME U-Pb monazite ages (550 Ma–520 Ma, Shiraishi *et al* , 1994, Asami *et al* , 1997) from the LHC The mean age of 583 Ma is close to the Rb-Sr whole rock age of a single

Table 4 *Difference of whole rock isochron ages between Sm-Nd and Rb-Sr systems for middle Proterozoic to early Paleozoic igneous rock-origin metamorphic rocks from Gondwana super-continent*

Place	Rock type	Sm-Nd Wr.Iso Age (Ma)	Rb-Sr Wr.Iso Age (Ma)	Time interval* Age (Ma)	References
E Antarctica (Lutzow-Holm Complex)					
Cape Hinode	Meta-trondhjemite	1016 ± 62**	974 ± 78**	42	Shiraishi et al (1995)
Oku-iwa Rock	Hornblende biotite gneiss	674 ± 22	583 ± 56	91	This study
E Antarctica (Sør Rondane)					
	Enderbitic gneiss	978 ± 52	961 ± 101	17	Shiraishi & Kagami (1992)
			950 ± 6***	28	
India (Eastern Ghats)					
	Opx granulite	1023 ± 93	958 ± 16	65	Shaw et al (1997)
	Leptynite	1464 ± 63	1366 ± 75	98	Shaw et al (1997)
S Africa (Namaqualand)					
	Granitic gneiss	1118 ± 148	1131 ± 62	-15	Yuhara et al (2001)

* Time Interval = (Sm-Nd whole rock isochron age)-(Rb-Sr whole rock isochron age) This calculation does not take account of error of age ** recalculated except sample "74010113 (Shiraishi *et al*, 1995)", *** recalculated using three felsic rocks (1503D, 1602D, 2502A Shiraishi and Kagami, 1992) from a single outcrop Data sources Shiraishi and Kagami (1992), Shiraishi *et al* (1995), Shaw *et al* (1997) Yuhara *et al* (2001) Wr Iso, whole rock isochron, Opx, orthopyroxene

outcrop of East Ongul Island (574±128 Ma, Shibata *et al*, 1986) and Breidvågnipa (576±39 Ma, Shimura *et al*, 1998) although they have large uncertainties The Sm-Nd whole rock isochron age of 674±22 Ma of the HB gneiss is definitely older than the Rb-Sr whole rock isochron age

Though we had tried to obtain metamorphism ages using the Rb-Sr whole rock system, we have no reliable ages indicating that metamorphism occurred, even for the samples collected from a single outcrop Dickin (1995) and Shimura *et al* (1998) also emphasized that isotopic equilibrium in the Rb-Sr whole rock system was not attained under metamorphism even during a high-temperature condition However, metamorphism accompanied by partial melting is not that case (Owada *et al*, 1991, 1997, Kagami *et al*, 1995, Shimura *et al*, 1998)

Two interpretations of the two ages of 583±56 Ma and 674±22 Ma are considered on the basis of the chemical behavior of Sm-Nd and Rb-Sr *Case (1)* Difference of closure temperature between Sm-Nd and Rb-Sr whole rock systems *Case (2)* Granodioritic precursor was initially formed at *ca* 670 Ma and granodioritic magmatism took place by refusion of the precursor at *ca* 580 Ma

Case (1) Sm-Nd and Rb-Sr whole rock ages for the same rock samples are not always identical because of the difference of chemical behaviors of the two systems There are not many reports defining reliable Rb-Sr and Sm-Nd isochrons even for the unmetamorphosed igneous rocks The Sm-Nd and Rb-Sr whole rock ages using identical rock samples from middle Proterozoic to early Paleozoic igneous-origin metamorphic rocks occurring in the Gondwana super-continent are summarized in Table 4 The Sm-Nd ages are generally 100 Ma–20 Ma older than the Rb-Sr ages The mean Sm-Nd age of the HB gneiss from Oku-iwa Rock is 91 Ma older than the mean Rb-Sr age Though this time interval has not been strictly discussed by the authors, one of the possibilities is the difference of closure temperatures between both systems If this is the case, the Sm-Nd age of 674 Ma indicates granodioritic magmatism (950±100°C) and the age of 583 Ma indicates the closure temperature (*ca* 700°C, Harrison *et al*, 1979) of the Rb-Sr whole rock system However the closure temperatures of both systems, especially Sm-Nd, have not been clarified yet Even if the rocks had been affected by later metamorphism with temperature of $>$*ca* 700°C thereafter, the Rb-Sr whole rock system would not have been greatly disturbed (*e.g*, Kagami *et al*, 1995) Though isotopic analysis of the leucosome in the HB gneiss has not been carried out, if the rock plots on both isochrons of Sm-Nd and Rb-Sr systems, interpretation (1) will probably be accepted

Case (2) Initial $^{143}Nd/^{144}Nd$ ratio of the HB gneiss is 0 511921±0 000021, which corresponds to $+2\ 96 \pm 0\ 41_{(674\ Ma)}$ in terms of ε-notation Nd model ages using depleted-mantle (T_{DMs}) were calculated for the samples (Sp No 19, 20) with $^{147}Sm/^{144}Nd < 0\ 13$, which are *ca* 1100 Ma (Table 2) Sample No 23 also has similar T_{DM} (1160 Ma, Table 2) The mean T_{DM} of six samples except samples Nos 15 and 16 with extremely high $^{147}Sm/^{144}Nd$ ratios is *ca* 1200 Ma These T_{DMs} are younger than other areas of the LHC (*ca* 2850 Ma, *ca* 2400 Ma, 1450 Ma–1300 Ma, Yoshida *et al*, 1999) Based on generally accepted interpretation as to the T_{DMs}, initial formation of the granodioritic precursor took place at *ca* 1100 Ma, and fusion of the precursor occurred at *ca* 580 Ma because resetting of the Rb-Sr whole rock system was caused by melting In this interpretation, a special meaning for the age of 674 Ma is not found On the contrary, if the granodioritic precursor was derived from an enriched source, the T_{DMS} are meaningless, and the following interpretation is possible (first stage-*ca* 670 Ma) initial magmatism of granodioritic precursor, (second stage-*ca* 580 Ma) refusion of the precursor (owing to formation of granodioritic magma) with formation of leucosome in the HB gneiss Again, isotopic data for the leucosome are useful to decide the possibility of the second interpretation In this interpretation, the rock must be plotted not on the Sm-Nd isochron but on the Rb-Sr isochron with an age of 583 Ma

Thus. the possible interpretation as to the ages of 674 Ma and 583 Ma is either (1) or (2) We prefer interpretation (1) because the following systematic relations between Sm-Nd and Rb-Sr whole rock systems (Table 3) are generally recognized (a) the time interval between the two whole-rock systems is restricted within a certain time range (100 Ma–20 Ma), (b) the Sm-Nd ages are always older than the Rb-Sr ages Furthermore, according to interpretation (2), resetting or disturbance for the Sm-Nd system of the HB gneiss did not take place at all at 583 Ma Even so, the second interpretation is still possible because the Rb-Sr age of 583 Ma is close to the age of 576±39 Ma of migmatite from the Breidvågnipa (Shimura *et al* , 1998) The leucosome in the HB gneiss holds the key to the meaning of the two ages (674 Ma. 583 Ma) discussed above Thus, the interpretation of the two ages is still an open question

6 4 Age relations between Sm-Nd, Rb-Sr whole isochrons and U-Pb zircon

The U-Pb age data (with high-closure temperature) for the metamorphic rocks from the LHC are restricted in the range of 560 Ma–520 Ma and *ca* 620 Ma (SHRIMP zircon ages, 550 Ma–520 Ma, Shiraishi *et al* , 1994, *ca* 620 Ma, 560 Ma–520 Ma, Fraser, 1997, CHIME monazite age, 537 Ma, 533 Ma. Asami *et al* , 1997) Our result shows that the migmatite of Oku-iwa Rock was formed at 674±22 Ma or 583±56 Ma The former age is older than *ca* 620 Ma and definitely older than 560 Ma–520 Ma defined by U-Pb ages on zircons The U-Pb zircon system is reset under granulite-grade metamorphism or partial melting (Lee *et al* , 1997) Loss of radiogenic Pb in zircon is caused by continuous diffusion or through the influence of metamorphism (Attendorn and Bowen, 1997) Following these considerations, if the migmatite was formed at 674 Ma, the Oku-iwa Rock area was continuously kept at high temperature from *ca* 670 Ma to *ca* 500 Ma This speculation is consistent with the conclusion by Fraser (1997) on the granulite-facies metamorphic zone of the LHC, that is, high-metamorphic conditions persisted for 100 Ma from *ca* 620 Ma to 520 Ma On the other hand, if the migmatite was formed at 583 Ma, the age difference between 583 Ma and U-Pb zircon ages, especially 560 Ma–520 Ma, is not clear because the former seems to coincide with the latter within an error In order to strictly discuss the migmatization (and metamorphic) age for this area, more precise data by dating systems such as U-Pb zircon, Sm-Nd and Rb-Sr hornblende of the leucosome and HB gneiss are needed

7. Summary

Rb-Sr and Sm-Nd whole rock isochrons for the granitoids and HB gneiss distributed in the Oku-iwa Rock area, Lutzow-Holm Complex, East Antarctica were obtained for thermochronological history The results are as follows 674±22 Ma (Sm-Nd whole rock ısochron age of the HB gneıss), 583±56 Ma (Rb-Sr whole rock ısochron age of the HB gneıss), 485±50 Ma (Rb-Sr whole rock ısochron age of the Akaı-mısakı granıte mass) U-Pb zırcon ages of *ca* 620 Ma and 560 Ma–520 Ma have been reported from the Lützow-Holm Complex, they are ınterpreted as tımes of peak metamorphısm The 485±50 Ma of the granıte mass ıs ınterpreted as an ıntrusıve age judgıng from field observatıons Regardıng the two ages for HB gn (674±22 Ma, 583±56 Ma), the followıng two ınterpretatıons are possıble (1) Dıfference of closure temperature between Sm-Nd and Rb-Sr whole rock systems (2) Granodıorıtıc precursor of the HB gneıss was ınıtıally formed at *ca* 670 Ma and mıgmatızatıon accompanıed wıth formatıon of the leucosome took place by refusıon of the precursor at *ca* 580 Ma Varıous age determınatıons usıng U-Pb for zırcon, and Sm-Nd and Rb-Sr for hornblende as to the leucosome and HB gneıss, holds the key to the solutıon of these two ages

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